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Publication Date
2010

Peer reviewed

The design tool and detailed user notes are available at: www.cbe.berkeley.edu/research/ufad_designtool-download.htm

Cooling Load Design Tool For UFAD

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For most of the past 10 to 15 years as underfloor air distribution (UFAD) has attracted growing interest and achieved market penetration, design engineers have had to develop their designs, make load calculations, and conduct energy simulations without the benefit of accurate and standardized design tools and energy models for UFAD systems.

Almost all energy and load calculation methods in widespread use by the industry today are not able to represent (without the use of workarounds) two distinguishing aspects of the thermal performance of UFAD systems under cooling operation:

- Room air stratification: cool supply air delivered by floor diffusers interacts with space heat loads to produce higher temperatures at ceiling level and cooler temperatures near the floor. Most models assume a well-mixed uniform space temperature.
- Underfloor air supply plenums: as the cool supply air from the air handler flows through the plenum, heat is transferred from both the concrete slab (in a multistory building) and the raised floor panels to the plenum air, resulting in most cases in temperature gain (thermal decay). Most models simply ignore heat gain to supply air in both plenums and ducts.

Recently, the situation has been improved with the release in April 2009 of version 3.1 and all subsequent versions of EnergyPlus,[1] a publicly available whole building energy simulation program capable of modeling the more complex heat transfer processes, like those found in UFAD systems. While EnergyPlus is certainly capable of being used to make load calculations, from a practical point of view it is important to develop a simplified load calculation procedure for designers. Previously a spreadsheet-based cooling airflow design tool for interior zones was described by Bauman, et al.[2] In this article, we present an updated and more complete version of the simplified tool. The design tool and detailed user notes are available at: www.cbe.berkeley.edu/research/ufad_designtool-download.htm.

About the Authors

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Review of Previous UFAD Design Tools

Only a limited number of cooling airflow design methods have been described for UFAD systems. Most have adopted concepts from the closely related stratified environments produced by displacement ventilation.[3]

In this regard Loudermilk[4] proposed a method based on the separation of the conditioned space into two distinct horizontal layers, a lower zone containing primarily cool fresher air, and an upper zone containing warm more polluted air. He assumed[4] that the height of the lower zone was equal to the vertical throw height of the floor diffusers, while in a subsequent similar approach described by Bauman,[5] the height was set equal to the "occupied zone."

In both methods, the determination of the required cooling airflow quantity is based on the assignment of convective heat gains occurring above the separation height into the upper zone, allowing this portion of the space cooling loads to be isolated from the lower zone where they would impact comfort conditions.

Several recognized limitations exist in these UFAD cooling load design tools. First, all previous methods were based on adding up the convective portion of design heat sources to represent the instantaneous cooling load in the zone. Computation of cooling load is complicated by the radiant exchange between surfaces and thermal mass in the zone.[6] Accounting for the time delay associated with the absorption of radiant heat transfer by thermal mass and subsequent rerelease by convection into the zone is a major challenge in cooling load calculations. The sum of all space instantaneous heat gains at any given time does not necessarily (or even frequently) equal the cooling load for the space at that same time.[7] For these reasons we have used EnergyPlus with its fundamental heat balance calculations in the development of the new design tool described later.

Second, the cool underfloor air supply plenum in multistory buildings in combination with room air stratification produces several new heat transfer pathways leading to significant quantities of heat entering the underfloor plenum. Dynamic and steady-state modeling research has shown that on average 20% to 40% of the total room cooling load is transferred into the supply plenum, leaving only about 60% to 80% that must be removed by airflow through the room.[8,9] The amount of heat entering the underfloor plenum directly influences the design cooling airflow rate and the occupants' thermal comfort. Finally, although there is reliable data describing how to split heat gain into radiant and convective components,[10] there is no research-based guidance on how to assign loads to the upper and lower zones of the room.

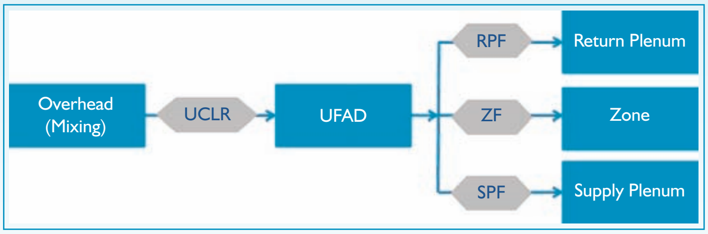

***Figure 1:** Flow diagram of design tool showing transformation from cooling load calculated for an overhead mixing system into a UFAD cooling load, and divided between the supply plenum, zone (room), and return plenum.*

Development of Design Tool

Figure 1 shows a flow diagram of the calculation process of the design tool. The approach taken for the design tool development was to focus on accounting for the differences between standard overhead (OH) mixing systems and UFAD systems. The tool does not calculate the UFAD cooling load from scratch, but instead uses as an input the cooling load calculated for the same building under design with an OH system. In this way, using a familiar load calculation tool the designer can account for such factors as building shell construction, orientation, and climate.

As shown in Equation 1, the tool transforms the design cooling load calculated for an OH system (CL_{OH}),[6,7] into the design cooling load for a UFAD system (CL_{UFAD}) using a correlation equation for UCLR, "UFAD cooling load ratio."

$$CL_{UFAD} = CL_{OH} \times UCLR \qquad (1)$$

The total UFAD cooling load is then split into three fractions; supply plenum (SPF), zone or room (ZF), and return plenum (RPF). It is the fraction (ZF) of the cooling load remaining in the room that is used to determine design cooling airflow rates, as a function of user inputs for diffuser supply air temperature, diffuser type and number, room setpoint temperature, and other key parameters. The diffuser supply air temperature is a function of the plenum configuration, plenum inlet temperature, and the fraction (SPF) of cooling load assigned to the supply plenum.

The four transformations shown in *Figure 1* were developed by conducting a matrix of design-day, EnergyPlus (v3.1)[1] simulations of a three-story prototype office building. EnergyPlus performs a fundamental heat balance calculation and contains UFAD-specific algorithms that have been validated based on extensive laboratory testing.[11,12]

The simulation study investigated the following nine parameters: floor level (ground, middle, top), zone (interior, north, south, east, west perimeter), structure type (light, medium, heavy), plenum inlet temperature, internal heat load, climate (seven locations), plenum configuration, window-to-wall ratio, and presence of carpet. Therefore, the design tool can be applied to a wide range of building types and climates. Full details are described by Schiavon, et al.[9]

Previously, it was thought that total cooling loads for UFAD and OH systems are nearly identical, meaning that UCLR would equal 1. However, recent energy modeling research has demonstrated that they are different.[9] As an example, *Figure 2* shows a comparison between the predicted cooling load profiles for OH and UFAD systems for five zones of a middle floor for a Baltimore, summer design day. The internal and external heat gains are almost the same (negligible differences due to different room temperature profiles) for the two systems, but the cooling load removed by the HVAC system is different. We believe that this is probably due to:

- In the OH system, part of the heat is stored in the thermally massive slab during the day and released at night when the system is off. Schiavon, et al.,[13] showed that the mere presence of the raised floor reduces the ability of the slab to store heat, thereby producing for the system with a raised floor higher peak cooling loads compared to the system without a raised floor.
- The airflow through the supply plenum tends to remove heat from the concrete slab and the raised floor panels.

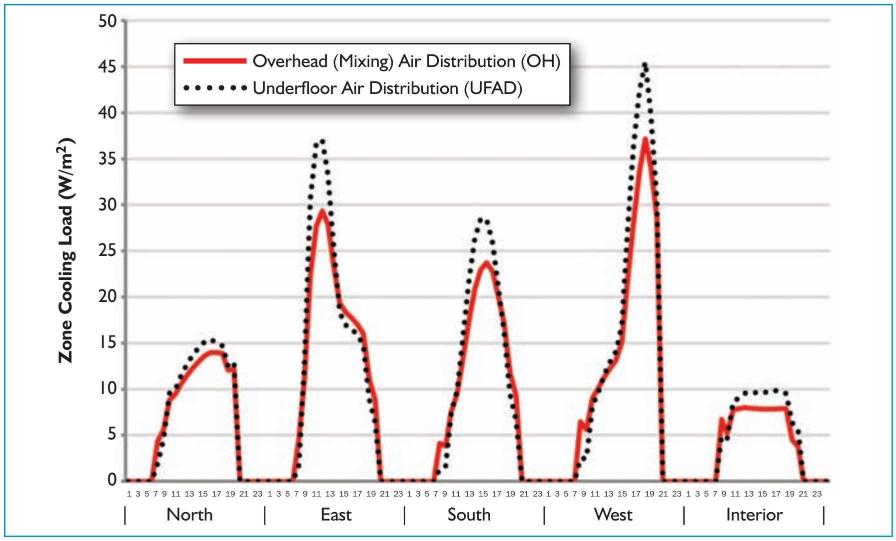

Figure 2: Design day cooling load profiles for overhead (mixing) and UFAD systems for five zones of the middle floor of a three-story office building in Baltimore. The HVAC system operates from 5 a.m. to 7 p.m.

The difference in cooling loads between OH and UFAD is also evident in the core zone that is not affected by solar radiation (*Figure 2*). The correlation equation for UCLR captures these differences, although their impact on annual energy consumption is expected to be insignificant.

A full description of the model equations, calculation procedures, and other assumptions used in the simplified UFAD cooling load design tool are presented by Schiavon, et al.[14]

Design Tool Description

A spreadsheet-based calculation procedure to predict the design cooling load and airflow rate for both interior and perimeter zones of a typical multistory office or other commercial building using underfloor air distribution has been developed.

The tool allows the user to select from four different plenum configurations that represent a range of design practice. *Figure 3* shows schematic and plan views of two of these options: series and reverse series. Both represent an open plenum design that serves the interior and perimeter zones of the conditioned space. In the series configuration, supply air from the air handler is first delivered to the interior portion of the plenum, where it gains some heat, and then

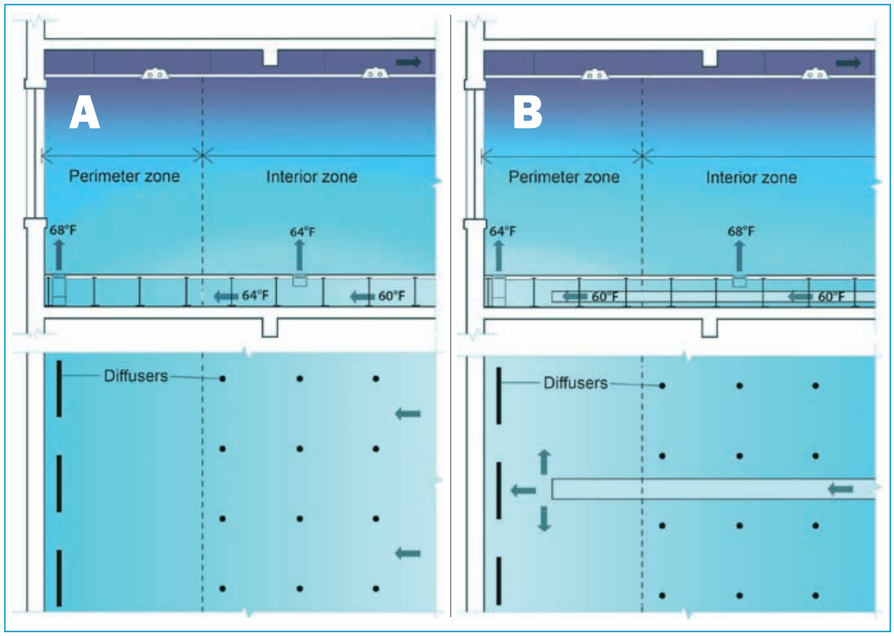

Figure 3a: Series plenum configuration. Figure 3b: Reverse series plenum configuration.

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passes on to the perimeter portion of the plenum. The reverse series represents a configuration where the supply air first enters the perimeter zone (by ductwork or shaft location) before entering the interior zone.

The other two plenum options include: common (the open plenum is assumed to be well-mixed and delivers the same average diffuser discharge temperature to both interior and perimeter zones); and independent (the plenum is assumed to be subdivided into separate interior and perimeter zones, each supplied with its own selectable supply air temperature).

The design tool predicts the room air temperature profile based on the fraction of the cooling load assigned to the room, room setpoint temperature, the type and number of diffusers, diffuser discharge temperature, and calculated airflow rate. The simplified stratification models have been previously described for interior zones[2] and new correlations for perimeter zones have been added based on full-scale laboratory testing.[12] Three of the most common floor diffuser types are modeled in the tool:

- Interior swirl diffuser;
- Interior and perimeter square VAV directional diffuser that automatically varies the ratio of time between when the diffuser is fully open versus when it is fully closed; and
- Perimeter linear bar grille.

Parameter	Interior	Perimeter
Room Height, ft	9	9
Floor Area, ft^2	3,500	1,500
Floor Level	Middle Floor	Middle Floor
Diffuser Type	Swirl	Linear Bar Grille (48 in.)
Number of Diffusers	20	14
Design Cooling Load Calculated for a Mixing System, $Btu/h \cdot ft^2$	9	24
Design Average Temperature in the Occupied Zone, °F	75	75
Estimated Category 2 Leakage, cfm/ft^2	0.05	0.05
Setpoint Temperature of Air Entering Supply Plenum, °F	63	n/a
Number of Occupants	20	n/a
Zone Orientation	n/a	South
Length of the External Wall of the Perimeter Zone, ft	n/a	100

Table 1: Design input parameters for the modeled UFAD system (series plenum).

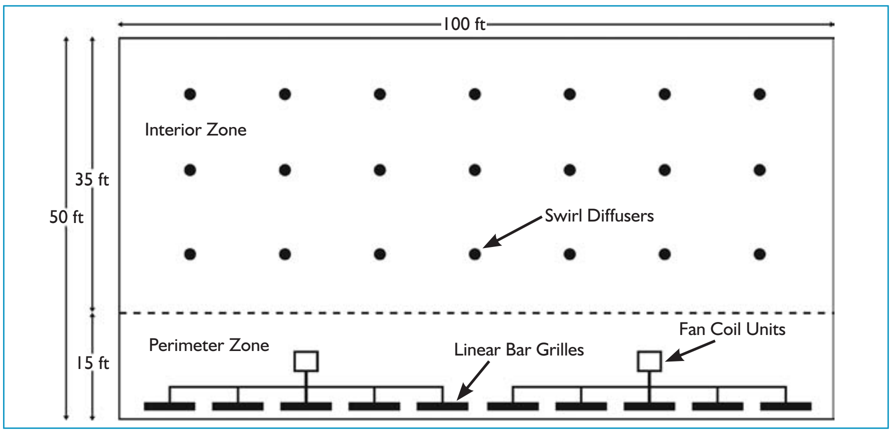

Figure 4: Floor plan for design tool example showing diffusers and underfloor fan coil units.

The design tool also accounts for the cooling contribution of Category 2 air leakage (leakage from plenum to room), for which the user can input an estimated value.

The design tool is suitable for application to typical office and commercial building construction with 4 in. to 8 in. (0.1 m to 0.2 m) thick uninsulated structural slabs, raised access floor with carpeting, and ASHRAE/IESNA Standard 90.1-2004 compliant building envelope. In its current form, the tool allows only one type of diffuser per zone. The tool has not been verified for use with high-ceiling spaces (e.g., auditoriums, theaters).

Design Tool Example

To demonstrate the capabilities of the UFAD design tool, an example of a 5,000 ft^2 (464 m^2) office space is presented. The design input parameters are summarized in *Table 1* for a series plenum. *Figure 4* shows a plan view indicating that air is delivered through swirl diffusers in the interior zone and linear bar grilles in the perimeter (number of diffusers will vary for different cases described below).

Figure 5 presents the temperature profiles for the two zones being considered as generated by the design tool. The profiles also graphically represent the amount of temperature gain (thermal decay) within the plenum. Note that for the series configuration, the air from the air handler enters the interior zone plenum at 63°F (17.2°C), where it warms up to 66.5°F (19.2°C). This warmer air is delivered into the interior zone (room) and also into the perimeter portion of the plenum, where it gains additional heat up to 69.8°F (21°C). The predicted room air temperature profiles allow the following parameters to be easily determined: (1) average occupied zone temperature setpoint equals 75°F (24°C); (2) vertical temperature difference between head and ankle heights for comparison with the maximum acceptable limit of 5.4°F (3°C) specified by ASHRAE Standard 55-2010; and (3) temperature at the standard thermostat height of 4 ft (1.2 m). The results indicate that the 4 ft (1.2 m) thermostat should be set to 76°F (24.4°C) to ensure an average occupied zone temperature of 75°F (24°C) in the more heavily stratified interior zone.

Detailed design tool results from the previous example are listed for Case 1 in *Table 2,* as well as several additional cases, which are discussed next.

- **Case 1** Demonstrates the impact of thermal decay in a series plenum. The high diffuser supply air temperature in the perimeter results in increased airflow and reduced stratification. For purposes of determining the minimum number of diffusers for peak design loads, the usual approach is to select enough diffusers so that each diffuser is operating at or just below its design airflow rate. However, in the interior zone with 20 occupants, a common, and preferred, design approach is to assign at least one swirl diffuser per person; i.e., per workstation. In Case 1 this results in only 64 cfm (30 L/s) (compared to design airflow of 80 cfm [37.8 L/s]) for each swirl diffuser, thereby contributing to increased stratification.

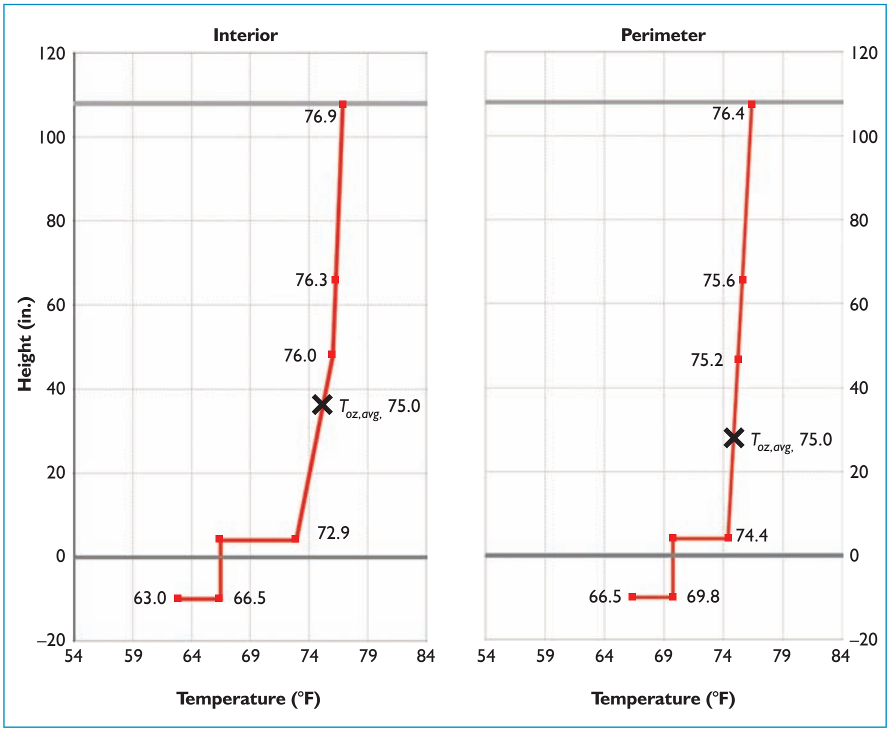

***Figure 5:** Predicted temperature profiles for interior & south perimeter zones for example in Table 1.*

- **Case 2** For this and other cases listed in *Table 2,* the design conditions are the same as those listed in *Table 1,* except for changes in plenum configuration, diffuser type and number, plenum inlet temperature, and average occupied zone temperature setpoint, as indicated. Identical to Case 1, except the number of swirl diffusers in the interior zone was reduced to bring the airflow per swirl diffuser up to its design value (77 cfm [36.3 L/s]). This has only a small impact of slightly reducing stratification and slightly increasing the zone airflow rate.
- **Case 3** Demonstrates the impact of using reverse series plenum configuration. The reverse series plenum delivers cooler air to the perimeter, resulting in a reduction in airflow of nearly 50%, with increased stratification. Due to the higher plenum temperature and higher airflow rate in the interior, the number of swirl diffusers must be increased to 40. It is likely that this configuration with warmer interior zone diffuser discharge temperatures will also provide comfort improvements in the interior zone, which can sometimes experience overcooling since there is no means of providing heat (outside of internal loads).
- **Case 4** Identical to Case 3, except the number of linear bar grilles in the perimeter was increased (thereby reducing vertical throw) until the maximum vertical temperature stratification limit was just met (5.2°F [3°C]). This produced the lowest combined total airflow for both zones for all cases in *Table 2,* except Case 6, and demonstrates the potential advantage of developing perimeter diffusers having reduced vertical throw.
- **Case 5** Demonstrates the impact of a common plenum assumption. The common plenum assumes that the incoming air is mixed equally in the interior and perimeter portions of the plenum, and delivers the same average diffuser discharge temperature in both zones. This configuration may be a better model for designs with higher plenum inlet velocities that create greater mixing.
- **Cases 6 and 7** A comparison of results for these two cases demonstrates the potential error in design airflow calculations if plenum thermal decay is ignored and each plenum zone is defined independently. In Case 6, the plenum inlet temperatures were reduced until the calculated diffuser supply air temperature for both zones was 67°F (19.4°C). This results in an extremely low airflow rate through the interior plenum (normally, the series plenum allows the total airflow serving both zones to pass through the interior portion) and requires the plenum inlet temperature to be set to 54.9°F (12.7°C). The results for Case 7 show what would happen if a designer assumed that 67°F (19.4°C) air leaving the air handler is the same thing as 67°F (19.4°C) air entering the space through the diffusers. Due to thermal decay, the predicted total airflow rate for Case 7 is nearly double that for Case 6.
- **Case 8** Identical to Case 1, except the average occupied zone temperature setpoint was increased by 2°F (1.1°C) to 77°F (25°C), which still falls within the acceptable range for operative temperature specified by ASHRAE Standard 55-2010 for summer clothing. The higher setpoint results

Case	Plenum Configuration[2]	Interior Zone						
		Plenum Inlet Temperature (°F)	Design Airflow (cfm/ft²)	ΔT_{OZ}[3] (°F)	Interior Diffuser			
					Type	No.	SAT[5] (°F)	Airflow Per Diffuser (cfm)
1	Series	63.0	0.42	3.4	Swirl	20	66.5	64
2	Series	63.0	0.43	2.8	Swirl	17	66.5	77
3	Reverse Series	65.4	0.95	1.0	Swirl	40	71.1	79
4	Reverse Series	65.5	0.96	1.0	Swirl	40	71.1	80
5	Common	63.0	0.60	1.9	Swirl	25	68.9	76
6	Independent	54.9	0.45	2.9	Swirl	20	67.0	70
7	Independent	67.0	1.15	0.8	Swirl	48	71.8	80
8[1]	Series With 77°F Setpoint	63.0	0.35	4.7	Swirl	20	67.1	53
Case	**Plenum Configuration[2]**	**Perimeter Zone (South)**						
		Plenum Inlet Temperature (°F)	**Design Airflow (cfm/ft²)**	**ΔT_{OZ}[3] (°F)**	**Perimeter Diffuser**			
					Type[4]	**No.**	**SAT[5] (°F)**	**Airflow Per Diffuser (cfm)**
1	Series	66.5	2.68	1.2	lin-48	14	69.8	282
2	Series	66.5	2.68	1.2	lin-48	14	69.8	282
3	Reverse Series	63.0	1.44	2.7	lin-48	8	65.4	261
4	Reverse Series	63.0	1.34	5.2	lin-48	12	65.5	161
5	Common	63.0	2.29	1.5	lin-48	12	68.9	279
6	Independent	62.0	1.76	1.8	lin-48	9	67.0	285
7	Independent	67.0	2.85	1.2	lin-48	15	70.1	280
8[1]	Series With 77°F Setpoint	67.1	2.30	1.4	lin-48	12	70.9	282

[1] Average occupied zone temperature setpoint for Case 8 is 77°F.
[2] See the Design Tool Description section for definitions of plenum configurations.
[3] ΔT_{OZ} = Temperature difference between head height, 67 in., and ankle height, 4 in.
[4] lin-48 = 48 in. linear bar grille.[14]
[5] SAT= Average diffuser supply air temperature.

***Table 2:** UFAD design tool results for floor plan shown in Figure 4. Middle floor; interior and south perimeter zones; interior zone cooling load (for OH system) = 9 Btu/h·ft²; south perimeter zone cooling load (for OH system) = 24 Btu/h·ft²; average occupied zone temperature setpoint = 75°F; Category 2 leakage = 0.05 cfm/ft².*

in a 15% reduction in total airflow to the interior and perimeter zones.

Acknowledgments

We would like to gratefully acknowledge the support for this research by the California Energy Commission Public Interest Energy Research (PIER) Buildings Program and CBE at UC Berkeley.

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